Brilliant, Coherent, Far-Infrared (THz) Synchrotron Radiation

The 'THz-Gap'

First reports on terahertz (THz) waves were published in Physical Review about 100 years ago by E. F. Nichols and H. Rubens from the University of Berlin. Similar to X-rays, THz-radiation can be used to ‘x-ray’ matter and detect hidden structures. Since engineers and researchers have recognized the potential of THz-radiation for imaging, spectroscopic and microscopic methods in solid state physics, biology, and medicine, interest in more powerful THz sources has grown.

THz-radiation is part of the electro-magnetic spectrum between electronically feasible microwaves and thermal black body radiation. Between these limits no powerful radiation has been available until recently. This region of the electromagnetic spectrum was therefore called the 'THz-gap'. The gap can be closed by thermal sources and more recently also by fs-table-top-lasers, but both sources are not particularly powerful. The only powerful sources so far have been free electron lasers or diodes. These sources, however, show a small bandwidth and hence are not useful for spectroscopic applications.

LINACs and Rings

Coherent synchrotron radiation (CSR) is a tool which overcomes these limitations. It offers powerful and broadband radiation in the THz-range. For the first time CSR was observed 1989 in Japan at Tohoku-300-MeV-LINAC. Recently an average power of 20 W was reported from the LINAC at Jefferson Laboratory, USA. CSR was also detected at some electron storage rings in the last years, but only as bursting radiation, indicating that bunch instabilities are involved in the emission process.

During the past few years, BESSY has developed a new technique to generate stable, coherent sub-THz and THz-radiation from the BESSY II electron storage ring in collaboration with the DLR [1]. THz-radiation is emitted by relativistic electrons radially accelerated by magnetic fields, as a part of the synchrotron radiation spectrum ranging from X-rays to THz-radiation. Normally, the phases of the electro-magnetic waves are not correlated and the power of the radiation is linearly increasing with the number of radiating electrons. In this incoherent radiation process the emitted THz power is low.

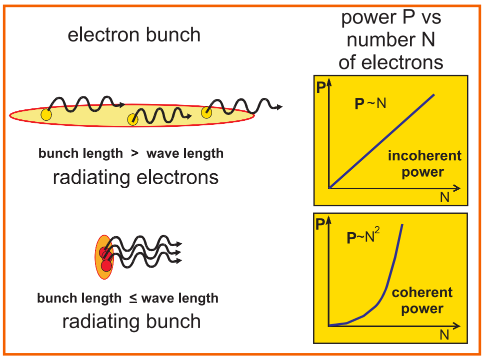


Fig. 1: Superposition of waves. Long bunches emit incoherent waves with random phase relation. Short bunches behave as a macroparticle and emit coherent waves at equal phase (left part of the figure). The resulting power grows linearly with the number of electrons for the incoherent case and the coherent intensity grows with the charge of the macroparticle (right part of the figure).

How to make Coherent Synchrotron Radiation

For the transition from incoherent to coherent emission process, three length parameters have to be considered: bunch length, radiation wavelength, and cutoff wavelength. For radiation with wavelength longer than the bunch, phases of the waves become independent of the emission point within the bunch and all phases become equal. The bunch can be considered as a single macroparticle, as sketched in Fig. 1. These waves add up coherently. Their field intensity grows linearly and their power quadratically with the number of electrons involved leading to a dramatic change in the emitted power since there are 10^8 to 10^9 electrons involved in this process. Fig. 2 shows the synchrotron radiation pattern with the coherent emission part included. The cutoff of the vacuum chamber sets a limit to this process.

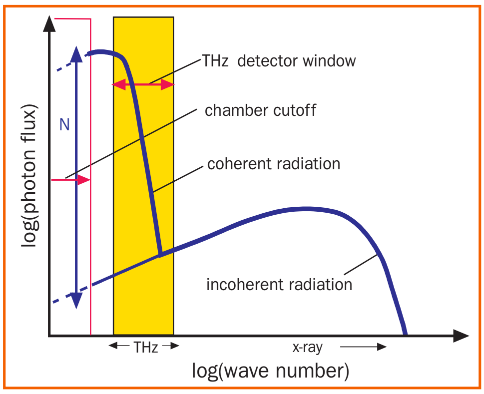


Fig. 2: Coherent and incoherent spectra. The synchrotron radiation spectrum shows a dramatic increase of photon flux in the long wave length range, if the coherent radiation is no longer shielded by the vacuum chamber. This additional increase is proportional to the number N of electrons involved.

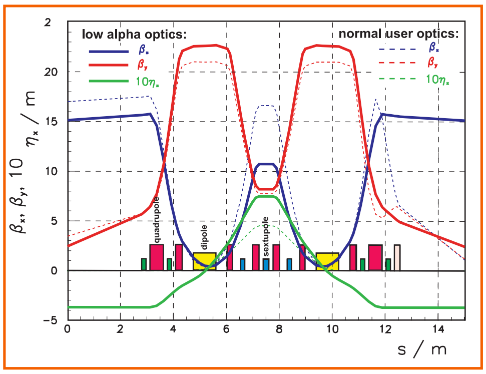


Fig. 3: 'Low alpha' optics. Comparison of the optical functions of 'low alpha' optics for bunch length manipulation and the normal user optics. The 'low alpha' optics changes the dispersion function (green) inside the dipoles in an appropriate way. α is defined as the change of the orbit length L per momentum p change ($\alpha = \delta L/L) / (\delta p/p)$.

Only if the waves are shorter than the cut off wavelength they can propagate in the chamber demanding sufficiently short bunches.

At the BESSY storage ring a 'low alpha' optics is applied to compress the bunches and to generate CSR as a stable non-bursting process. A comparison between the normal user optics and the 'low alpha' optics is shown in Fig. 3. The differently tuned dispersion function inside the ring dipoles reduces the transverse machine optics parameter α, the 'momentum compaction factor'. With the reduced α the orbit length in the storage ring becomes nearly independent of the electron momenta. In the limit $\alpha = 0$, the orbit length is independent of the particle momentum. All particles circulate with the same revolution time and the optics becomes isochronous. Also with a reduced α, the longitudinal oscillation of the electrons around the bunch center takes longer and the oscillation amplitude becomes smaller. This leads to compressed bunches, where the length shrinks in proportion with $\sqrt{\alpha}$, i.e. a 25-times smaller α leads to 5 times shorter bunches (Fig. 4).

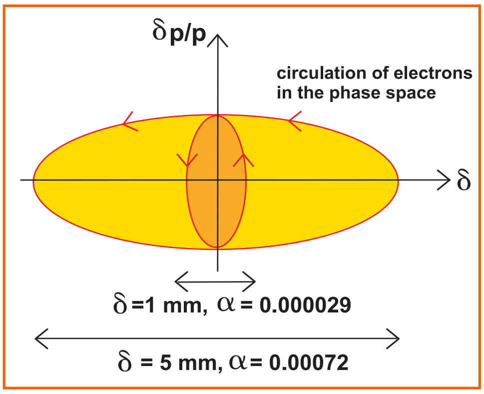


Fig. 4: Bunch compression. In a co-moving coordinate system electrons perform oscillations around the bunch center. In the 'low alpha' optics the oscillation amplitudes are reduced and the bunch is compressed. The momentum spread of $\delta p/p$ the electron beam stays unchanged.

The BESSY optics is very well suited for the required detuning of the beam optics to the 'low alpha mode'. The size of the radio frequency (rf-) buckets containing the electron bunches is defined by the rf-voltage, which has to be controlled very carefully during the detuning, because undersized buckets lead to the loss of electrons. These essential higher order optics corrections can be performed with the existing flexible sextupoles scheme.

In the normal user optics the rms (root mean square) value of the bunch length at low current is 5 mm and $\alpha = 7.2 \cdot 10^{-4}$. At approximately $\alpha = 6.5 \cdot 10^{-5}$ the bunch shrinks to an rms-length of 1.5 mm comparable to sub-THz wavelength and bunches become sufficiently shorter than the cutoff wavelength of the vacuum chamber. At this reduced bunch length a strong THz-power increase becomes detectable.

For CSR experiments typically a bunch length of about 1 mm and bunch currents of 50 µA are used. If all 400 buckets of the storage ring are filled the average current is about 20 mA and the life time of the stored beam is several hours. The radiation process is very stable. The emitted light is therefore very well suited for Fourier Transform spectroscopic applications.

Influence of the Ring Current

The bunch length is sensitive to the bunch current. Increased current leads to longer bunches but also to more CSR power. This indicates a bunch deformation away from a Gaussian shape, which results from an interaction of the bunch with its own CSR-field. Above a threshold current the interaction of the CSR-field with the bunch becomes so strong, that the emitted intensity is periodically modulated and finally changes into a chaotic bursting process. This unstable bunch dynamics and radiation process can be detected in the normal user and the 'low alpha optics', whereas the stable emission only occurs in 'the low alpha' mode.

The power of the emitted incoherent radiation is proportional to the average current, independent of α, whereas the coherent power scales completely differently. At the detection limit it grows nonlinear if α is further reduced and scales roughly with the square of the bunch current. However, due to bunch deforming and bunch lengthening effects the scaling is actually stronger than the square of the current. This nonlinear dependence on the beam current is a proof of the coherent emission process.

References:

[1] M. Abo-Bakr, et al., Phys. Rev. Lett. 88, 254801 (2002).

[2] M. Abo-Bakr, et al., Phys. Rev. Lett. (2003), accepted.

[3] W. C. Barry et al., Proceedings of the EPAC 2002, Paris, France.

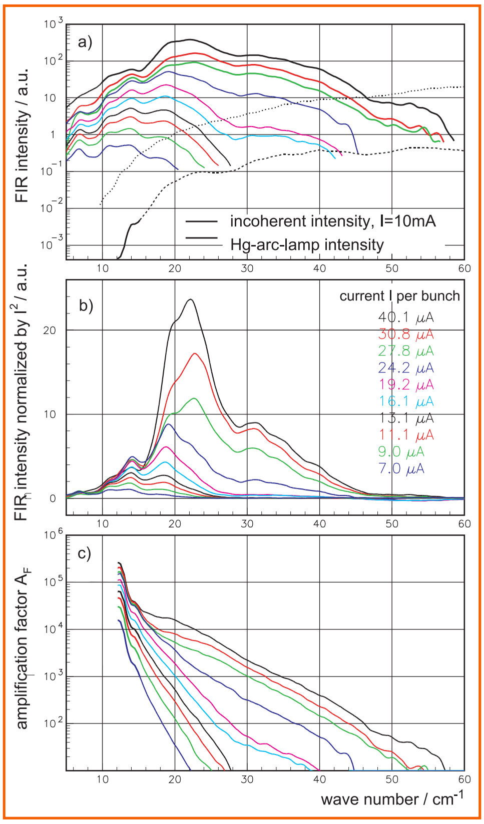
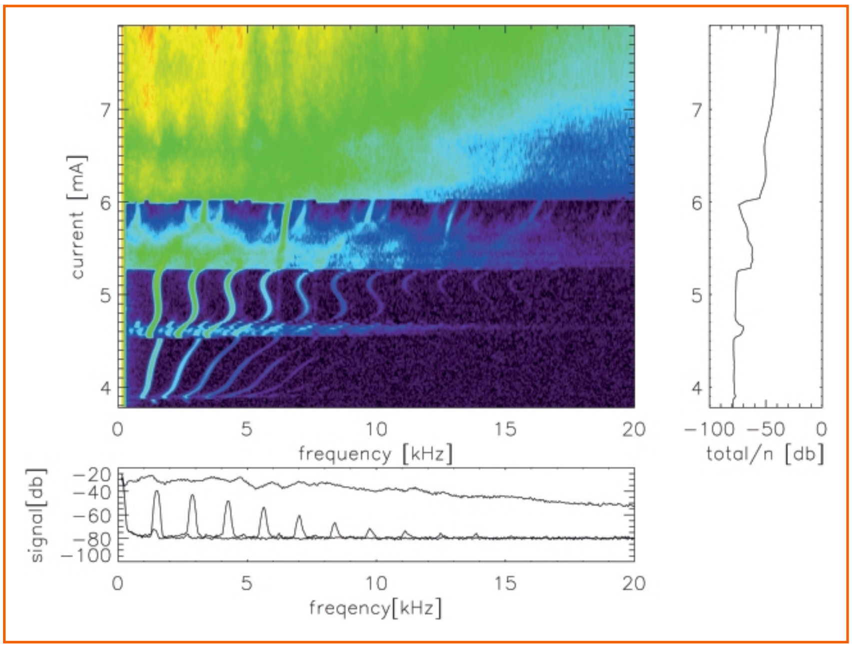


Fig. 5: CSR spectrum.
(a) The spectral content of the radiation measured by a Fourier transform spectrometer. The intensity is not corrected for transmission effects. In (b) the intensity is normalized by the square of the bunch current. The growth is stronger than the square of the bunch current, indicating bunch deformation effects.
(c) The amplification factor A_F is the ratio between coherent to incoherent intensity. The amplification by the coherent superposition of the waves becomes as large as 10^5. It is independent of the transmission efficiency of the setup.



New opportunities for BESSY User

The spectral quality of the CSR was characterized at the IRIS infrared beam line [2]. The detected power maximum is located between 10 to 20 cm^{-1} (0.5 to 1 mm wavelength). The intensity at larger wave numbers depends on the current per bunch. Additional current enhances the spectrum at larger wave numbers beyond 40 cm^{-1} at the expense of the stability of the emission process.

The incoherent spectrum in this frequency range, measured during the normal user optics shift shows very poor intensity and 10 times higher current is required to get reasonable signal strength. The ratio between coherent and incoherent spectra at the same average beam current is a measure of the power amplification due to the coherent emission process. The amplification factor is up to 10^5. This factor is used to estimate the strength of the coherent source, because the source intensity for the incoherent case can be calculated. In the wave number range from 12 to 50 cm^{-1} an average power of 1 mW is emitted into an angle of 60 x 40 mrad^2. During the unstable emission mode even more power is generated.

The THz radiation can also be used for diagnostics in beam dynamics. An example is shown in Fig. 6. During a single bunch shift and the normal user optics THz-radiation was applied to detect bunch instabilities. Depending on the bunch current, the emission process changes from a periodic to a chaotic busting process.

The technique applied to generate CSR offers new experimental opportunities in the THz range, to the scientific community. First THz experiments have already been performed at BESSY (see page 18). The technique might also be a starting point of a new class of dedicated storage rings for CSR [3] increasing the availability of powerful THz-radiation. Finally, the applied 'low alpha' optics is not only of interest for coherent radiation, it also offers the possibility of short bunches (at low current) for other applications, such as time resolved studies.

Fig. 6: THz-diagnostics of bunch instabilities.
Bunch instabilities are detected by the emitted THz radiation during single bunch shift with normal user optics. At about 4 mA, a periodic bursting is visible with frequencies of up to 5 kHz. With increasing current the periodic frequency pattern changes several times and eventually gives way to a chaotic pattern at 6 mA.
The panel shows the integrated intensity on the right. Cuts taken at three different currents show the frequency pattern as seen on the spectrum analyzer (lower figure).

Contact:
Godehard Wüstefeld
wuestefeld@bessy.de